MINIATURIZATION OF ATMOSPHERIC ENTRY PROBES: OPTIONS FOR FUTURE PLANETARY EXPLORATION MISSIONS

Austin R. Howard

University of Idaho, Moscow, ID, USA, austin.r.howard@gmail.com

ABSTRACT

Reducing the size, complexity, and mass of entry probes has the potential to greatly reduce the cost of collecting atmospheric/planetary science data. Additionally, small probes have the potential to provide a scientifically focused platform that can be produced and deployed in relatively large quantities, resulting in an increase in spatial and temporal resolution of the data delivered by probe missions. However, there exist certain technological barriers that need to be addressed before such missions gain wide spread acceptance in the solar system exploration community. This study offers a summary of the small probe concept, as well as a discussion of some of the challenges and advantages of applying such a concept.

Key words: Microprobe, Picoprobe, Planetary Probe, Mission Concepts.

1. INTRODUCTION

Exploration in general is a grand challenge, and the exploration of space is certainly not an exception. To explore the limitless bounds of space is to search for the answers to the key questions that have echoed in minds of humans since the beginning of time. Where did we come from? What is our destiny? Are we alone? To be human is to explore, to question not only the origins of life as we know it, but also the bounds of human ability. As explorers we face new challenges everyday, whether they be scientific, technical, or political. To overcome these challenges we must apply the lessons learned through centuries of trial and error, but we must also have the strength and insight to try out new strategies. After all, don't unique new challenges deserve unique new solution paths? As we extend ourselves through creative new interpretations of old images and data sets, we must also continue to develop ways of shedding light on the darkness of the unknown.

This study does not intend to argue that we replace any of our current exploration tools with micro-probe technology, rather the study suggests the addition of micro-probes[1] to our arsenal of exploration tools for the purpose of gaining new perspectives on our view of our solar system. There is no doubt that large Flagship class missions have a critical role to play in exploration. This fact can be clearly shown by simply reviewing the discoveries enabled by data collected from missions such as Galileo, and Cassinni. The size and diversity of large mission's payloads offers not only high quality science return, but also a context to help translate instrument data into knowledge and understanding of our universe. However, this understanding comes at the cost of a decade or more of development time and billions of dollars of investment money. It also comes with the inherent and unavoidable risk associated with a single large payload platform. This risk drives internal redundancy and safety margins up, resulting in the high cost, mass, complexity, and the extended design time associated with Flagship class missions.

An alternative, and supplementary, approach is to implement a large quantity of focused science payloads rather than one high quality platform with a diverse science package. This is the foundation of the micro-probe concept. Due to the small size and low mass of the micro-probe design it is conceivable to have dozens of spacecraft stowed away in a carrier vehicle in a configuration similar to that of a seed pod (Fig. 1). These vehicles could contain identical or diverse science payloads. The probes could be deployed at once or at specific predetermined intervals over both space and time as suggested by the Pascal mission team [6]. Another advantage to the small size and low mass is the ability to "piggy back" on larger missions, therefore extending the capabilities of our larger missions with minimal impact on the carrier spacecraft. This technique is suggested by several concept design teams including the Atromos team [7].

This study starts by looking back through recent history with the hope of answering the question, are we ready for a change? Then the study discusses the great potential that micro-spacecraft have to reveal new dimensions that can help us collect and interpret scientific data resulting in accumulation of knowledge and understanding of our universe. Finally, the study offers a short case study in

[1]For the purposes of this study, micro-probe is defined as a probe with a total mass under 10 kg and pico-probe is defined as a probe with a mass of 2 kg or less.

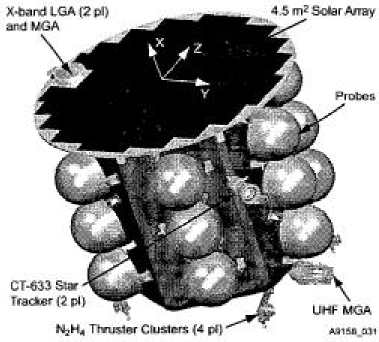


Figure 1: Pascal Probe Carrier Spacecraft [6]

the hope of sparking imagination and to hint at the possibilities such a platform could offer to the exploration of our solar system.

2. REVIEW OF MINIATURE PROBE DEVELOPMENT

The idea of multiple miniature space probes is not a new concept. In fact many concepts have been proposed and, and in the case of Deep Space 2 (DS II), have flown in deep space. Many of the proposed concepts have faded out of the strategic exploration plan for various reasons ranging from technological readiness to political priority shifts. However, the development of the DS II microprobe arguably demonstrated the feasibility of the miniature probe concept and also suggests that some (if not most) of the critical technologies required for integration of the concept into our exploration strategy are ready (or at least close). The following section offers a review of some of the important advancements of miniature probes by summarizing the accomplishments in the area.

2.1. Planetary Atmospheric Experiment Test

On June, 20th 1971 and instrumented atmospheric entry probe entered Earth's atmosphere. The probe was designated PAET (Planetary Atmospheric Experiment Test vehicle) and the purpose of the probe was to measure, in-situ, the composition and structure of the atmosphere (Fig 7a). Instruments included accelerometers (the help characterize the aerodynamics of entry), temperature and pressure sensors (to measure atmospheric temperature and pressure), a mass spectrometer (to characterize the composition of the atmosphere), and a radiometer (to sense emission from the probe shock layer at high speeds). Even though PAET entered Earth's atmosphere, the instruments were designed for use at other planets.

The experiments produced data that was used to map the thermal structure of the atmospheric from an altitude of 80 km. The radiometer and the mass spectrometer both functioned properly but problems with the sampling system on the mass spectrometer produced incorrect composition data [4].

The PAET vehicle was one of the first atmospheric entry probes and serves as a reference geometry and instrument suite for in situ planetary atmospheric science. See Table 1 and Figure 1 for a mass and diameter comparison. The insights gained from PAET continue to be important to the design of entry probes today.

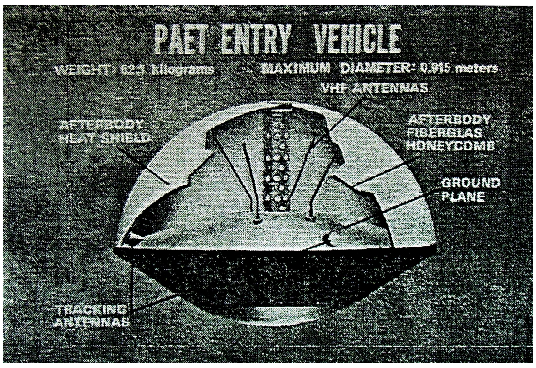


Figure 2: PAET configuration [10]

2.2. Deep Space II

Deep Space II was the second New Millennium planetary mission. The New Millennium Program is a NASA technology development program designed for the purpose of validating, in space, key technologies needed for high priority science missions. The Deep Space II (DS-II) mission was designed at Jet Propulsion Laboratories (JPL) for the purpose of enabling network science missions and demonstrating the concept of a highly miniaturized and specialized planetary probes [8].

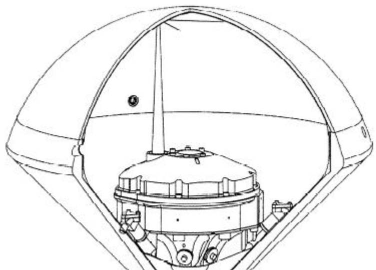


Figure 3: DS-II cut away view[8]

Two separate and identical 3.6 kg micro-probes (Fig 3) were attached to the Mars Polar Lander spacecraft which launched January 1999. Upon approach the micro-probes separated from the carrier vehicle and entered the Martian atmosphere. The probes were each instrumented with a descent accelerometer (to characterize the properties of the Martian atmosphere), sun sensor (to sense the relative position of the sun once on the Martian surface), a penetrator which included an impact accelerometer (to characterize impact properties of the Martian surface and sub-surface), a water sensor (to detect subsurface water) and a soil thermometer (to characterize the temperature and thermal conductivity of the Martian surface) [8] (Fig 4).

Unfortunately, JPL was unable to make contact with either of the micro-probes after contact with the Martian surface. The origin of the failure remains a mystery. Even though the mission failed to produce any scientific or engineering data on Mars, the DS-II micro-probe design serves as a reference design for future micro-probes and the lessons learned by the design team will be invaluable to future micro-probe designers.

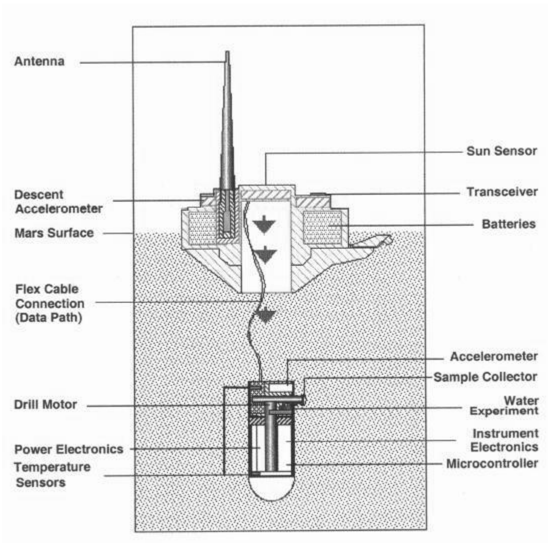


Figure 4: DS-II instruments [8]

2.3. REBR and PREP

The Re-Entry Breakup Recorder (REBR) is a probe concept based on the concept of a spacecraft "black box", or critical flight data logger, on various manned and unmaned space missions. Spacecraft "black boxes" have proved to be a challenge to design due to the requirement of surviving the harsh planetary entry environment. In recent years, Aerospace Corporation in El Segundo, California has been developing the REBR pico-spacecraft for the purpose of recording critical flight data upon reentry in Earth's entry. Aerospace Corp. has developed a demonstration prototype that was tested on a high altitude balloon launch in cooperation with the Montana State University in June 2006 [3]. The engineering prototype tested had a weight of about 1.4 kg with a diameter of 0.3 m (Fig. 5). The final REBR design is projected to have a mass under 1 kg with a diameter of 0.3 meters. The payload includes accelerometers, rate gyros, temperature sensors, GPS, and special thermal sensors developed by the NASA Ames Research Center. REBR uses the global Iridium Satellite Network to send sensor data to a receiving station in Colorado during the mission.

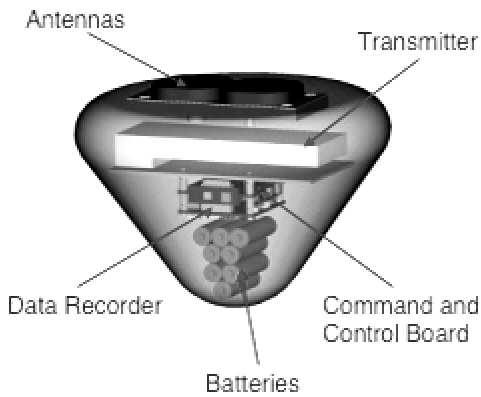


Figure 5: REBR diagram, image credit: Aerospace Corp. [1]

REBR is designed to be attached to satellites and other spacecraft from launch through the end of mission. Upon re-entry, REBR will "wake up" and start logging data during entry. REBR will descend through Earth's atmosphere sending data to receiving stations real time for the purpose of tracking entry debris (Fig. 6 REBR mission concept). Data can also be used to help scientists and engineers understand the entry environment and the behavior of space debris as it enters the atmosphere. It is the hope of REBR designers to gather information that could be applied to improve future space craft design and reduce re-entry hazards [3].

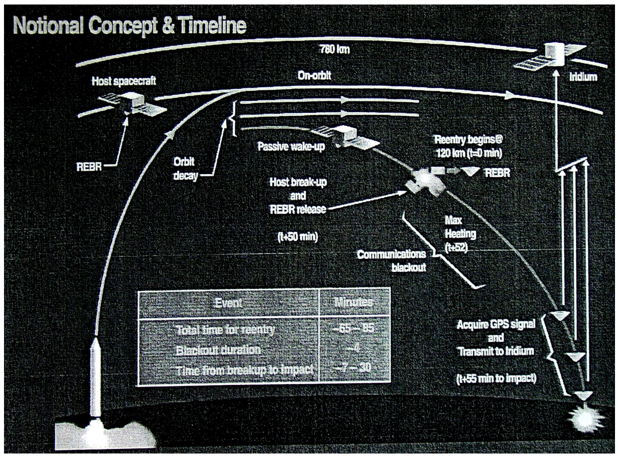


Figure 6: REBR mission concept, image credit: Aerospace Corp. [10]

A similar concept is the Pico Re-Entry Probe (PREP), which is simply a more general version of REBR. PREP could be a very cost effective and low risk test bed for key miniature probe technologies such as the Thermal Protection System (TPS). Like REBR, PREP would be launched on carrier vehicles such as Earth orbiting satellites or the Crew Exploration Vehicle. Because of the very low mass of PREP (projected to be around 850 grams with a diameter of 0.22m) [10], PREP could be launched on nearly any space mission with minimal impact on the carrier vehicle. In addition, the PREP concept relies on a carrier spacecraft to escape Earth's atmosphere, so the cost associated with launch would also be kept to a minimum.

The development of the REBR and PREP pico-probe concepts could launch a new era of miniature spacecraft, not only for Earth based applications, but for other planetary exploration applications as well. Development of these probes would mature miniature space probe technology, and would enable the cost and risk effective implementation of this idea that will become a critical part of the solar system exploration strategy.

3. DISCUSSION OF MINIATURE PROBES

The following section discusses the miniature probe concept in terms of risk, cost, and science return. Miniature probe mission concepts are discussed in general terms. In order to characterize specific mission concepts in terms of these factors, a more focused study is required.

3.1. Risk

In some instances adding total system redundancy is simply not practical on large spacecraft. One example of such a case is the Galileo high gain antenna which did not deploy properly. Galileo had a secondary low gain antenna that was used to transmit data back to Earth. However, the consequence of relying on the low gain antenna was an average data rate over 2000 times smaller than the data rate obtainable via the high gain antenna [16, FAQ page]. The cause of the failure remains unknown and it greatly reduced the science returned by the Galileo spacecraft and nearly resulted in a complete mission failure. This example demonstrates the inherent risk[2] in relying on large complex spacecraft to collect science data.

One advantage to the miniature probe concept is the ability to have in essence parallel components in a system. Consider one spacecraft as a component in a system designed to collect science data in deep space. If 20 miniature spacecraft are launched and 70% of the spacecraft fail to perform their function, the mission can still be successful with science data collected from 14 of the spacecraft.

For example, suppose the probability of mission success of a typical spacecraft is 97%. This means that the single spacecraft must be 97% reliable for the given mission life. Now suppose the same science objectives can be accomplished with a miniture spacecraft. If three miniture spacecraft are used the reliabilty can be represented by equation 1 [5], where P_{sc} is the system reliability assuming the mission can be successful if one "component" spacecraft completes its function and that all spacecraft failures are independant of all others, P_s is the reliability of a single spacecraft and N is the number of spacecraft.

$$P_{sc} = (P_s)^N + \sum_{K=1}^{N-1} \frac{N!}{K!(N-K)!}(P_s)^{N-K}(1-P_s)^K \tag{1}$$

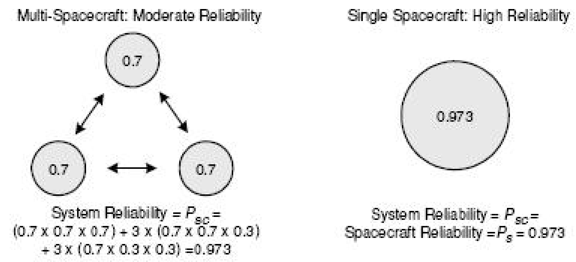


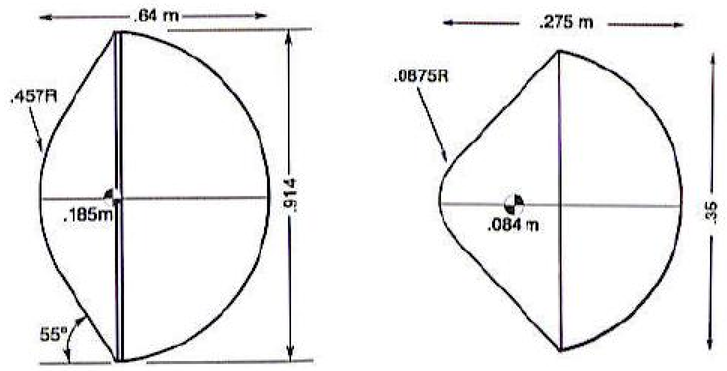
Figure 8: System reliability of one versus multiple spacecraft [5]

For this example, the miniature spacecraft only needs a reliability of 70% to obtain the sytem reliability of 97% (Fig. 8). Since cost has a non-linear relationship with reliability, it is possible that the three moderate reliability spacecraft could offer a cost effective approach. However, it is outside the scope of this study to further investigate this topic. Another advantage to the multiple spacecraft concept is that if more than one spacecraft succefully fulfill thier mission, additional science data is produced by the mission. Now imagine applying this principle to 20 or 100 spacecraft.

3.2. Cost

As mentioned in section 3.1, cost is a function of reliability [5]. This is due to the high levels of testing required to obtain high reliability components. Also the market for highly reliable components is limited in size so often it is difficult to find vendors to supply the extremely high quality parts required to obtain the desired spacecraft reliability. The vendors of high quality components often make one or two products at a time. Strict testing and quality requirements combined with low volume translates to the high costs traditionally associated with spacecraft. With the miniature spacecraft concept, it is conceivable to use reliability components as demonstrated by the example in the previous section. If the required reliability is low enough, it is conceivable to design micro spacecraft with commercial off the shelf components (COTS) potentially resulting in a drastic reduction in component costs. Since miniature spacecraft would be produced in relatively high quantities, an assembly line strategy could be used during fabrication and assembly which could drive cost down further.

[2]Risk is defined as the product of the the probability of failure and the severity of the system failure.



(a) PAET

(b) DS-II

Figure 7: Atmospheric probe comparison [2]

Table 1: Comparison of small planetary entry probes

-	PAET [4]	DS-II[2]	REBR (est.)[10]	PREP (est.)[10]
Date	1971	1999	In Development	In Development
Diameter (m)	0.914	0.35	0.3	0.22
Vehicle Mass (kg)	62.1	3.67	$\leq$ 1 (est.)	0.85 (est.)

In addition to the actual cost of hardware is the cost of launch. The cost of launch is in large part a function of the mass of the payload. Since the miniature spacecraft would be designed with a mass of 10 kg or less, they could be added to nearly any deep space mission to supplement the the carrier vehicle's science capabilities with minimum added cost. An alternate scenario is a mission entirely comprising miniature spacecraft. In this case the payload could be scaled up or down to enabling more flexibility when optimizing the launch vehicle selection.

3.3. Science Return

The miniature probe concept not only has the potential to drive cost and risk down, but in addition it has advantages with respect to science return as well. One such advantage is the ability to take advantage of multiple sample statistics when analyzing data. The uncertainty associated with single point measurements drives instrument requirements and therefore payload cost (and sometimes mass) up. One way to reduce uncertainty without changing the instrumentation is to take additional samples with the same instrument. Again, multiple spacecraft could take redundant measurements of the same target, or the space craft could take measurements of various targets distributed in both space and time. The specific concept of operations would depend on the science objectives.

Imagine attempting to understand the weather patterns on Earth with meteorology data from one site in California, USA. Even if the data was recorded with the best instruments available, it would be difficult to understand the global context. Multiple probes could land at sites distributed over the globe offering scientific insight that would be otherwise unobtainable. In fact certain science objectives require the use of a global network. Two examples of such areas of science are meteorology and seismology. Both require long term measurements from distributed sites over the globe. Mars seismology has been among the top science priorities for Mars since the 1970's [13], however no mission to date has successfully established a seismic network on Mars. Miniature probes could be the technology needed to establish such a network.

3.4. Technology Development

Power supply on miniature spacecraft is a challenge. Batteries and power generators comprise a significant fraction of the vehicle mass in small spacecraft. This is especially true for missions with extended surface lives. Traditionally, planetary entry probes have used batteries and landers have used either solar arrays or Radioisotope Thermoelectric Generators (RTG) as the primary power source. The solar power produced by solar solar arrays is proportional to the surface area exposed to sun light, requiring deployment devices which add mass and design complexity. RTGs have a high mass, cost, and create thermal complications that require large radiators to get rid of excess heat. These considerations point to batteries and/or novel power generation techniques such as milliwatt thermoelectric generators [15] for planetary entry probe application.

The primary strategy to reduce the mass of the power sub-system is to reduce the power required by the C&DH (Control and Data Handling) communications and thermal sub-systems and the spacecraft instruments. Many low power electronics are available on the consumer market. However, no low power electronics with the necessary Technology Readiness Level (TRL) are readily available (at least to my knowledge). This is a critical technology area that needs further development. Currently work is being done in this area and two example of active projects are the Micro-Inspector Avionics Module (MAM) [11] and Mars Proximity Micro-Transceiver [9].

The power requirements for direct to Earth communication are such that the miniature probe missions will have to rely on communication relays for most destinations in our solar system. Again this is a limiting factor and needs to be carefully addressed in each specific mission design. Another important technology area related to the communication sub-system is antenna design. Increasing antenna performance can also save power and their is some interesting research in genetic optimization of antenna design that could not only reduce power requirements, but also reduce the size and mass of antennas on miniature spacecraft [12].

In addition, limiting the mission life will also reduce the mass of the batteries required, especially when the design requires using primary (non-rechargeable) batteries as the main (or only) power source. The use of Radioisotope Heating Units (RHU) can also provide a relatively low mass thermal energy source that can be used to maintain the appropriate internal temperatures, thereby avoiding the use of electric heaters that would require extra battery capacity and electric power generation.

Miniaturization of instruments and electronics is continuing to transform the consumer and military electronics marketplace. Low cost MEMs technology is being applied to a range of instruments, enabling many conveniences and additional features on modern electronic devices. Examples include tilt sensors in digital cameras that automatically position pictures correctly when storing them in memory and instrumented frisbees to help understand the complex aerodynamics of an age old toy [14]. However, the ambient environment that these electronics are expected to operate in is very different from the space environment. The key question is what portion of these technologies can be applied to space exploration, and what is needed in order to adapt and transfer technology to enable the application of miniature space probes?

4. CASE STUDY: TITAN WINGED DECELERATOR

To illustrate the seemingly endless opportunities that the miniature probe platform could provide for planetary science, and in an effort to spark the imaginations of students and professionals alike, I conclude this study with a short case study of a Titan micro probe concept.

The year is 2028, the scientific discoveries of the Huygens atmospheric entry probe and the Cassini orbiter in addition to the success of the international partnership represented by the Cassini-Huygens mission have prompted a second visit to the Saturn planetary system. A entry probe containing a tightly stowed montgolfier balloon (Fig 9) and its payload approaches the largest of Saturn's moons and the only moon in the solar system with a dense atmosphere.

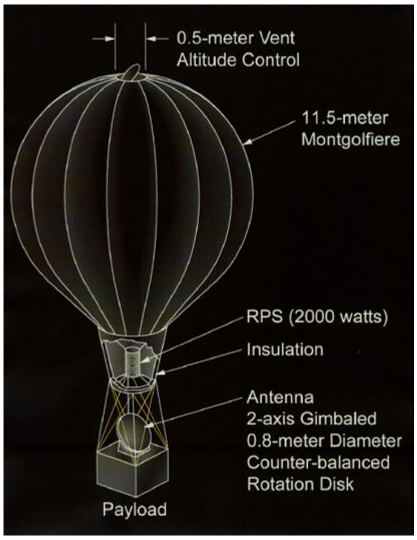


Figure 9: Titan mongtgolfier balloon

The primary science objectives Titan balloon called Hyperion (for the purposes of this study), are (a) to further understand the mechanisms of fluvial erosion and the drivers of the methane cycle, (b) to map the internal structure of titan and to determine if surface or sub surface liquid methane or water are present, (c) and to determine the wind/weather patterns in Titan's atmosphere. To accomplish these objectives, Hyperion carries a payload containing pressure/temperature sensors (to characterize Titan's atmospheric properties), gas chromatograph mass spectrometer (to characterize the composition of the atmosphere), a microphone (to record the acoustics of precipitation), ultra stable oscillator (used for radio occultation and wind characterization), and multiple cameras (to observe clouds and surface features).

At the same time the probe containing the balloon was entering Titan's atmosphere, 10 - 1 kg para-rotors (Fig. 10) were being distributed by a communications orbiter flying by Saturn's moon. A heat shield will protect the para-rotors in the first phases of the descent.

Once the aeroshell has slowed the descent of the pico-probes to a appropriate velocity, the para-rotors emerge from their cases. Each para-rotator will carry temperature/pressure/acceleration sensors (for characterizing atmospheric and surface properties), microphone (to sense subsurface seismic activity caused by tidal forces), and a liquid methane sensor. Each of the probes descend from high altitude and spin through the atmosphere to impact the surface. Aerodynamic contact with Titan's atmosphere will cause the para-rotor to spin rapidly. The dynamics of the para-rotors will be used to help characterize Titan's atmospheric properties. In addition the spinning motion will act as decelerator, allowing each probe to drift in the atmosphere and collect temperature and pressure data. Upon impact, the probes will plant themselves firmly in the surface of Titan.

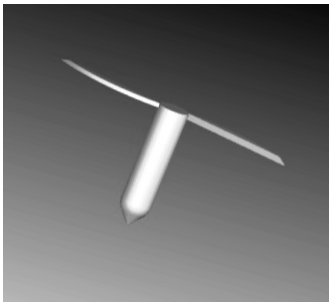


Figure 10: Titan Para-Rotor

Each probe will also be equipped with an RHU that will supply enough thermal power to maintain adequate temperatures within the probe for months. The probes will collect data and relay their findings to the balloon that is waiting in Titan's atmosphere. The scientific discoveries resulting in the pico-probe mission the first seismic and meteorological network on Titan's surface, revealed mysteries of the processes that help make Titan a fascinating and unique destination.

5. CONCLUSION

As we gaze up at the stars in the same way that the first philosophers, scientists and dreamers did thousands of years ago, searching with an unwaivering devotion for a purpose and an understanding of our origins and fate, we must also search for new ways to explore the unknown. The miniature probe platform is an enabling technology for high priority planetary science and has the potential to significantly reduce the cost of atmospheric science. In addition, miniaturization of entry probes also enables multiple probe deployments increasing temporal and spacial resolution of the science data return. Miniature probes cannot replace the large scale exploration missions, but rather play the role of a synergetic supplement to large missions as well as an enabling technology for network missions. The development of the Deep Space II microprobe in the 90's and the emerging pico-probe concepts suggest that miniature probes will play an integral part in future exploration missions and that the technologies required are nearly ready. The remaining technology development areas include low power electronics, miniature instrumentation and low mass power supplies. Strategic investments must be made to expand our exploration toolbox, allowing us to observe and explore our universe from continuously new perspectives, resulting in scientific discovery.

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